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Data reduction for the Spartan Camera

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- Outline
  - Design of observations
  - What was done for the Crab Survey
    - Use of IRAF & Mathematica
  - Instrument characteristics
    - Wavelength of narrow-band filters shifts with position
    - Calibration
    - Distortion-induced flat field
    - Astrometry
    - Light leaks
    - Bad pixels
    - Detector tiles
    - Saturation
    - Nonlinearity
    - Cosmic rays
    - Detector Noise
    - Normalization
  - Issues

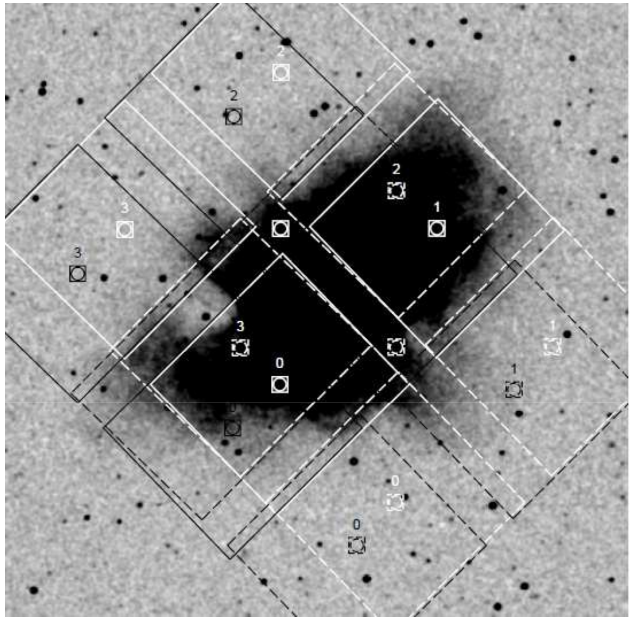
- Reducing data for Crab Survey, ApJS in press, arXiv1103.6043
- Instrument paper on Spartan in preparation for PASP

Crab Survey of H2—Design

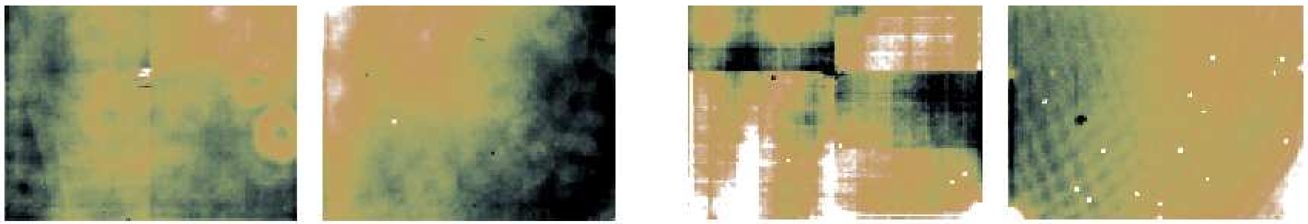
- Goal
  - Find molecular hydrogen in the ν=1$\rightarrow$0 S(1) line
  - Measure Brγ
- Observing principle: There are many problems that cannot be fixed by measurement. Remove them from the data by subtracting

$$\text{Target} - \text{Sky}$$

- Target A, A' (offset by 40"), B, B' (offset by 40")
- Sequence, which interleaves target & sky:
  - H2 (2121.8nm) 3min at A, A', B, B'
  - Cont 3, 3 min with same pattern
  - Brγ, 4.2min with same pattern
- Measure Persson calibrating star infrequently
  - 2MASS stars in the field turned out to be better.



Example of an effect that is removed without measuring



Ratio of sky flats K/H (left) and J/H (right)

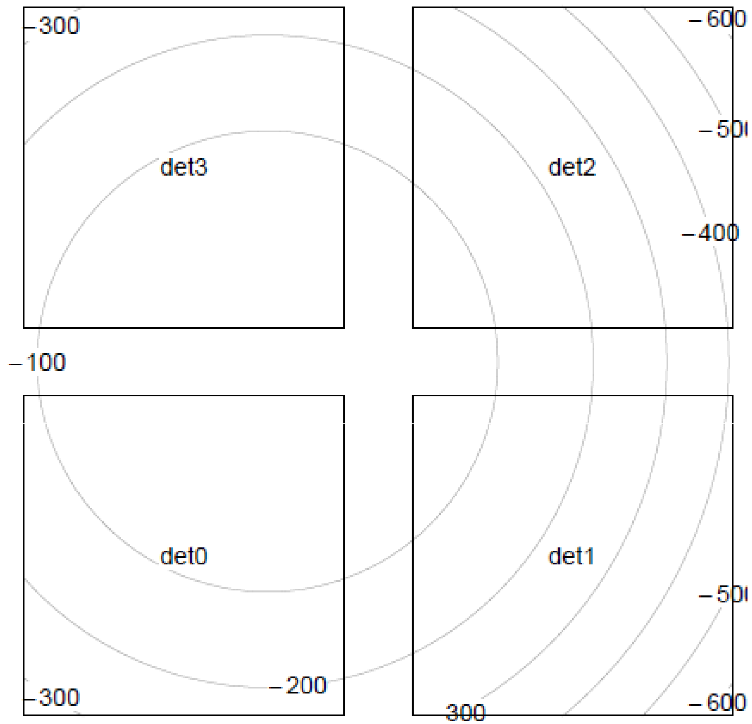
- The sky flats show problems (dust emission?, night sky lines at filter boundary?)
- Problems disappear in Target-Sky

Data reduction: mostly IRAF; some specialized routines written in Mathematica

- Fix detector tiles
  - Boundaries of 128×1024 tiles have an additive offset
  - fixDetectorTiles.nb (Mathematica)
- Convert world-coordinate system from SIP (Simple polynomial) to TNX to use IRAF
  - exportFITSHeader.nb & writeTNXHeader.nb
- Subtract light leak. More later.
- Remove cosmic rays
  - erodeCosmicRays .nb
  - IRAF cosmicrays & crnebula removed the centers of stars
- Find median of sky (IRAF)
- Find offset (msccmatch)
- Resample onto a rectangular grid (mscimage). Use a map of bad pixels
- Determine sky transparency and relative intensity (normalizeImages.nb)
- Combine ~130 image of each filter (imcombine)
- Remove low-level discontinuities by filtering in vertical & horizontal directions.

Filters: wavelength shift

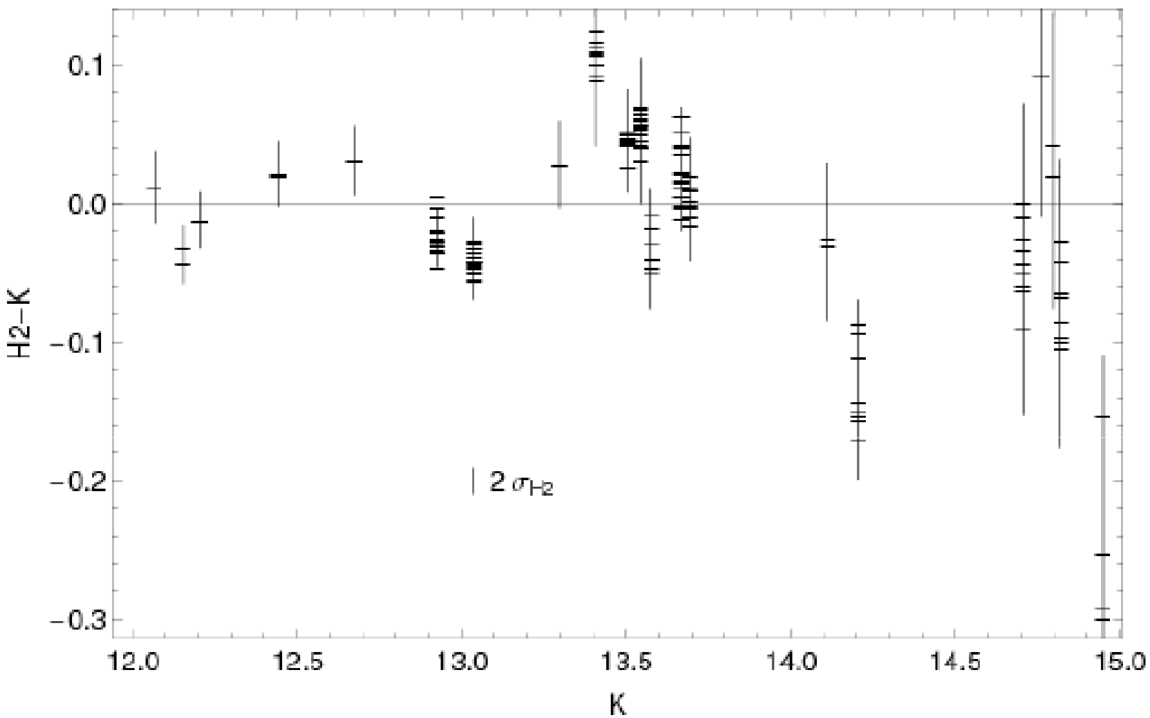
Contour plot of the velocity shift in km/s for the H2 filter. The negative shift means the filter is centered for a blueshifted source.



- Filters are at the pupil, where light rays are parallel. Incidence angle changes across the field.
- Wavelength shifts according to position of star in the sky.

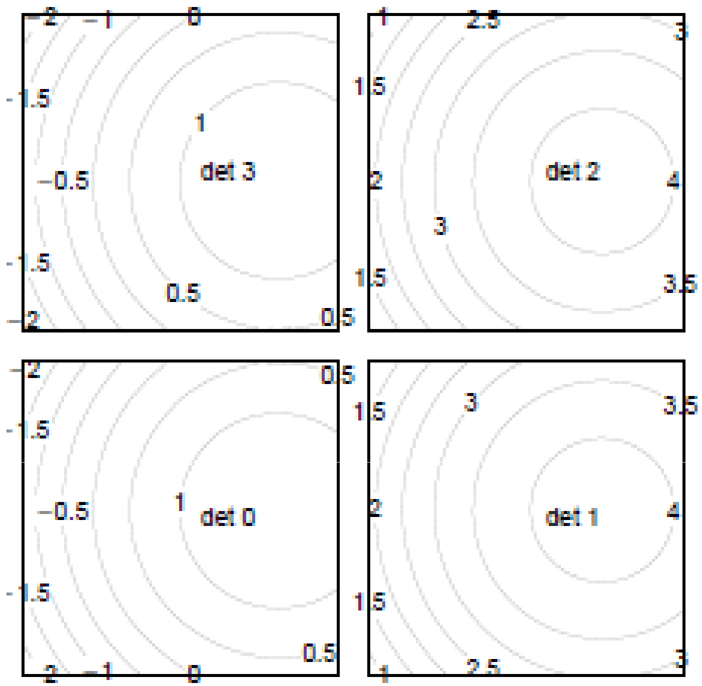
Calibration using 2MASS

Difference between the H2 and 2MASS K-band photometry of the stars used for calibration. The error bars account only for the error in the 2MASS photometry.



- Use 2MASS stars in the Crab to calibrate
  - Error of weighted mean is 0.003mag for H2 and 0.004mag for Brγ.
  - Use calibration of Vega, Kurucz model, & sun of Labs &Neckel

Distortion-induced flat



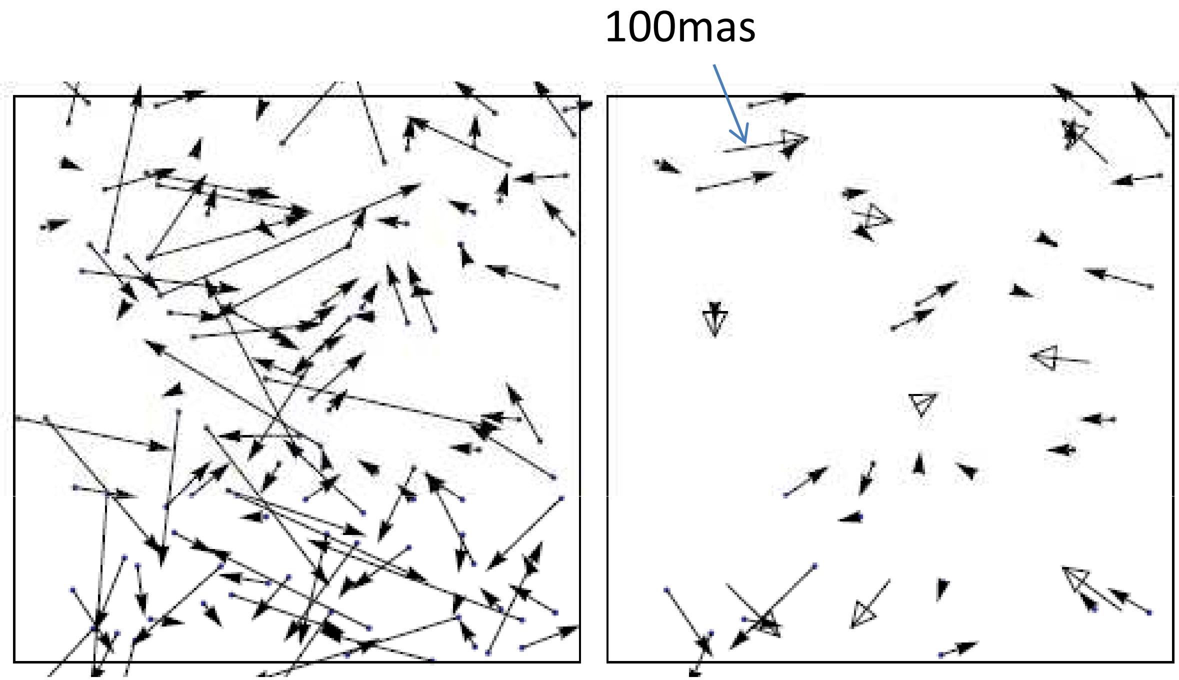
Distortion-induced flat field for the wide-field channel. The contours are in percent.

- Distortion means a pixel maps into a solid angle in the sky that varies.
- A field with uniform illumination is not flat.

Astrometry

- WCS in FITS header has
  - Distortion computed from the optical design
  - Translation, scale, and rotation measured in Dec 2009.
- WCS need to be shifted because of telescope pointing errors.
- The WCS has been checked against 2MASS catalog for one detector.

WCS checked with 2MASS



Offset between 2MASS positions and positions determined with DAOPhot scaled 100x. Left: Right: Clean stars, those which are not blended according to 2MASS and have no nearby neighbors in our image: Big arrows: average.

- Residual distortion exists. In corner where it is biggest,

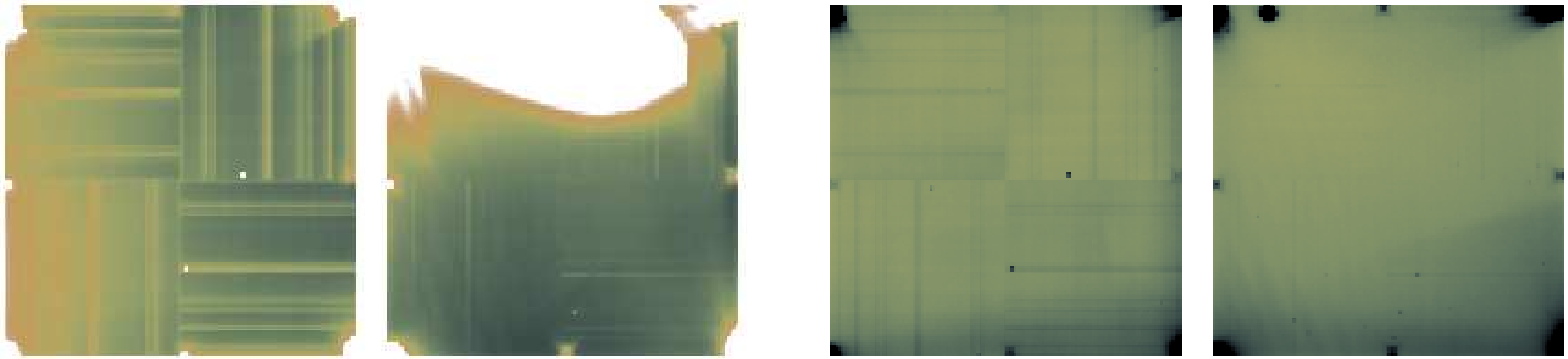
$$(dx, dy) = (95 \pm 24, -46 \pm 18)\text{mas}$$

$$(1.4 \pm 0.7, 0.7 \pm 0.3)\text{pixel}$$

Light leak

- Sources
  - Total
    - Measure with open focal-plane mask & a dark slide at the pupil.
  - Internal
    - Measure with closed focal-plane mask & use a dark slide at the pupil.
  - External=Total-Internal
- Temperature dependence
  - Approximately $T^3 \exp(-\frac{E}{k(T-25C)})$, E=hc/(2500nm) and T is the temperature of the telescope strut (key ENVTEI).
- Measure for one image per night and use the formula.

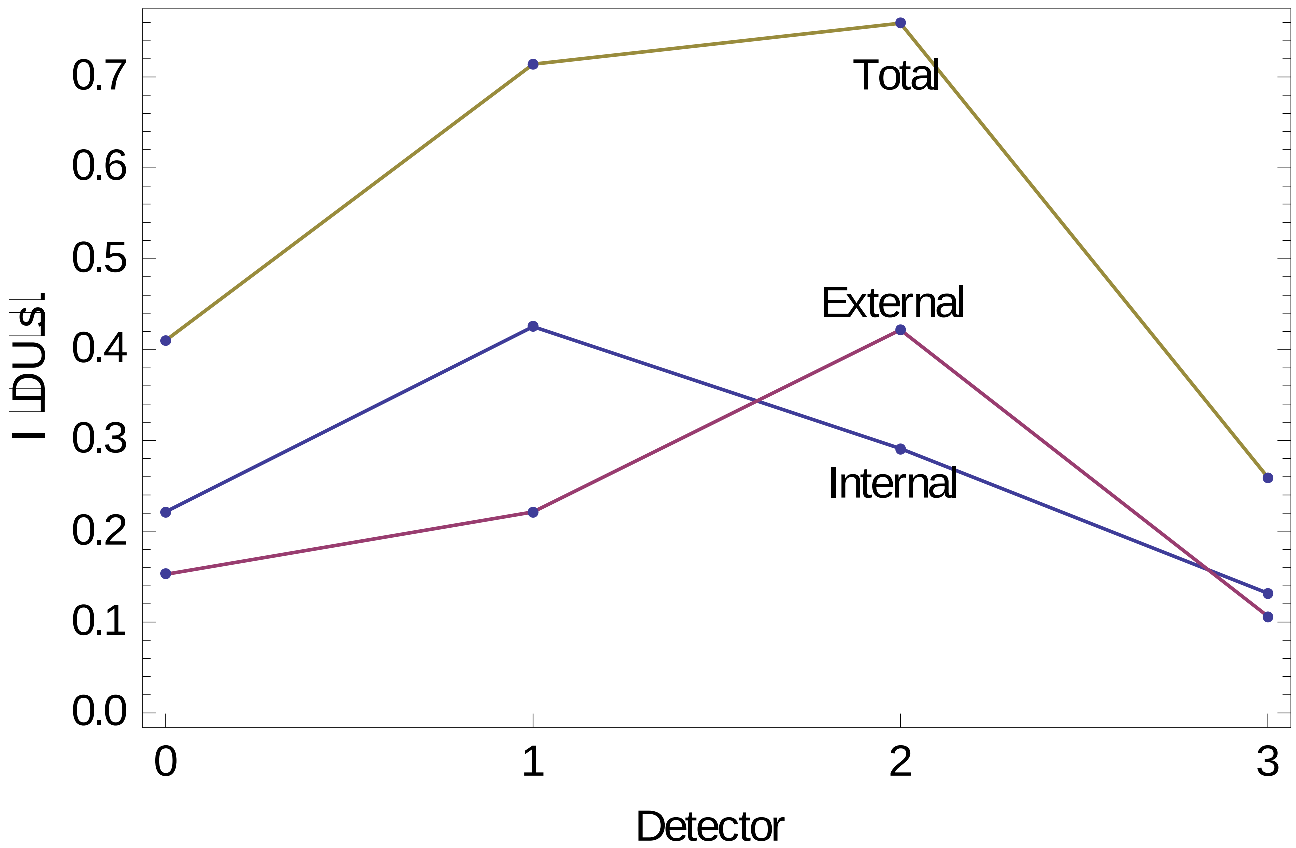
Signature of light leak



Internal (left) and external (right) light leak for detectors 0-3, ccw from lower left.

Intensity of light leak

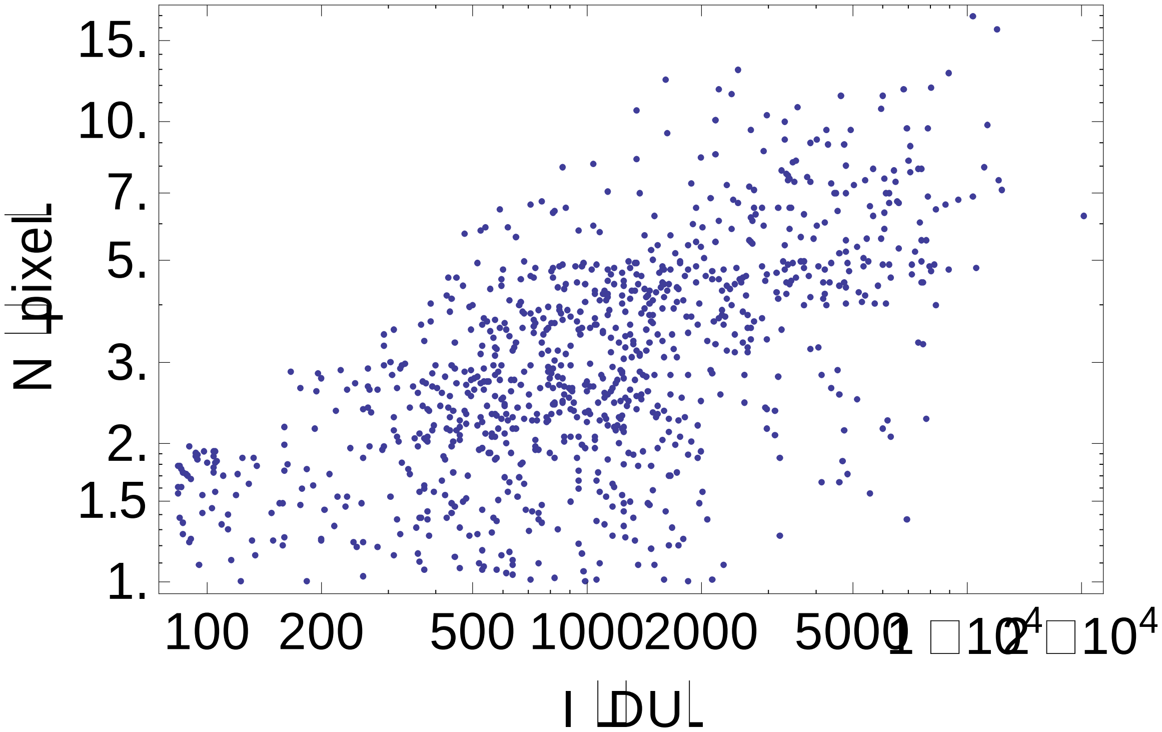
- Light leak is 0.3-0.8 DU/s.
- Light leak is 5-10% of sky for the H2 filter (2120nm)



Median intensity of the central ¼ of image

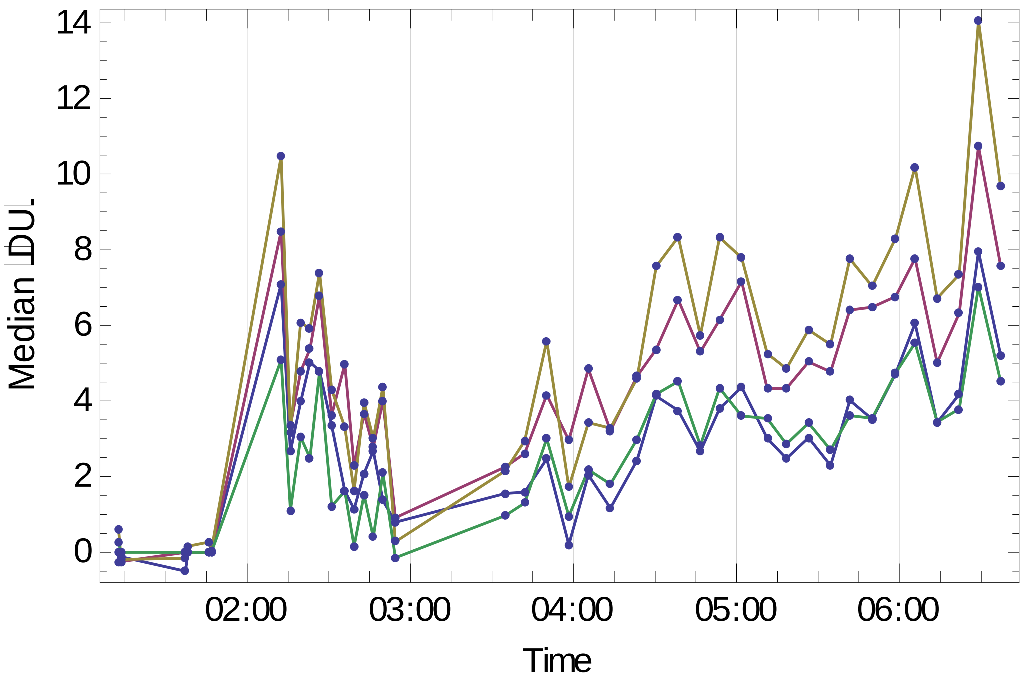
Cosmic rays

Number N of pixels affected vs intensity I of the cosmic ray for an H2 image of M1 with detector 3 with a 3-min exposure. N has been shifted by a random number between 0 and 1 for clarity.

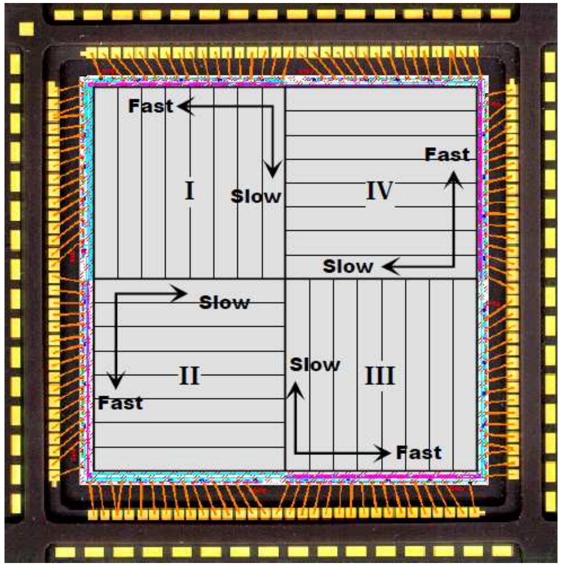


- erodeCosmicRays.nb "successively erodes the edges of a cosmic ray. On the first pass, it erodes the boundary of a cosmic ray. On subsequent passes, erosion causes the boundary to shrink." Designed not to eliminate centers of stars.
- Rate on a detector is 4Hz.

Detector tile pattern



Median of the tile edges for detector 0 for 25 Dec 2009. Quadrants: Lower-left: blue, lower-right: purple, upper-left: taupe, upper-right: green.

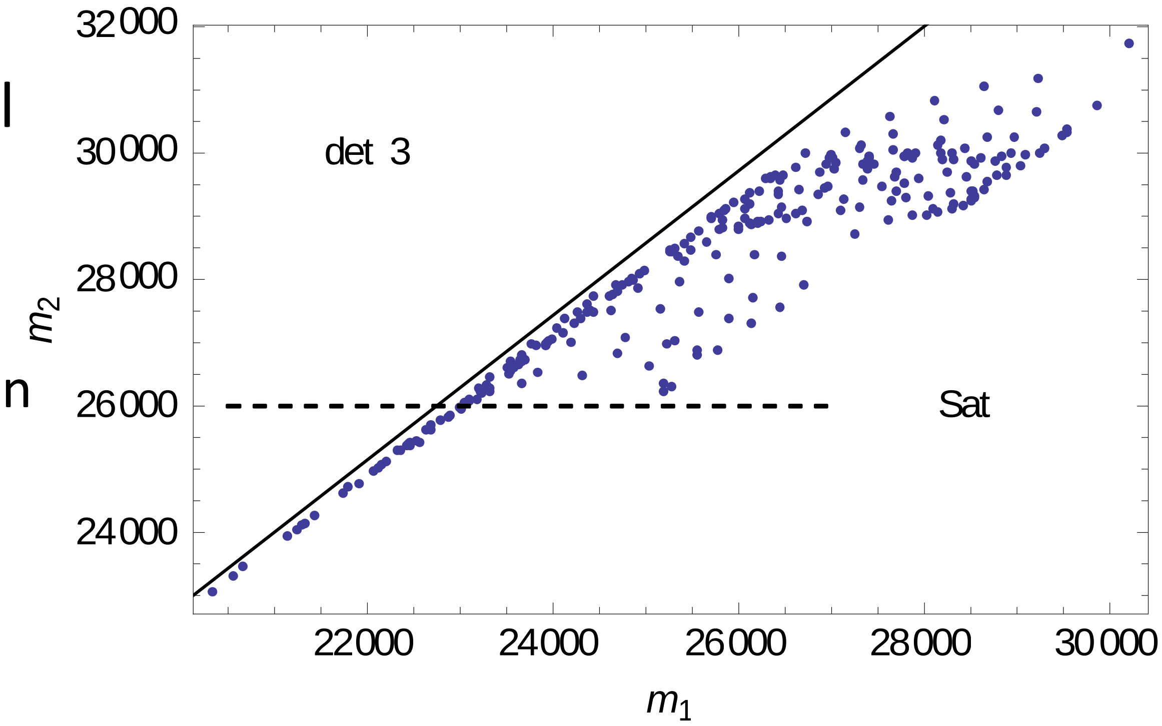


- Detector masks are made of 128×1024 tiles.
- Tiles are visible in the image.
- fixDetectorTiles.nb determines the depth and subtracts.
- Detector 0 is worst case. Pattern & non-linearity may have the same cause.

Saturation is not uniform

- Saturation measured for 128pixel×128pixel tiles.
- Saturation is not uniform.
  - Each pixel has its own transistor.
- Global saturation is defined to be the minimum over all tiles.

Detector	Sat. [kDU]
0	29.8
1	33.0
2	33.0
3	26.0

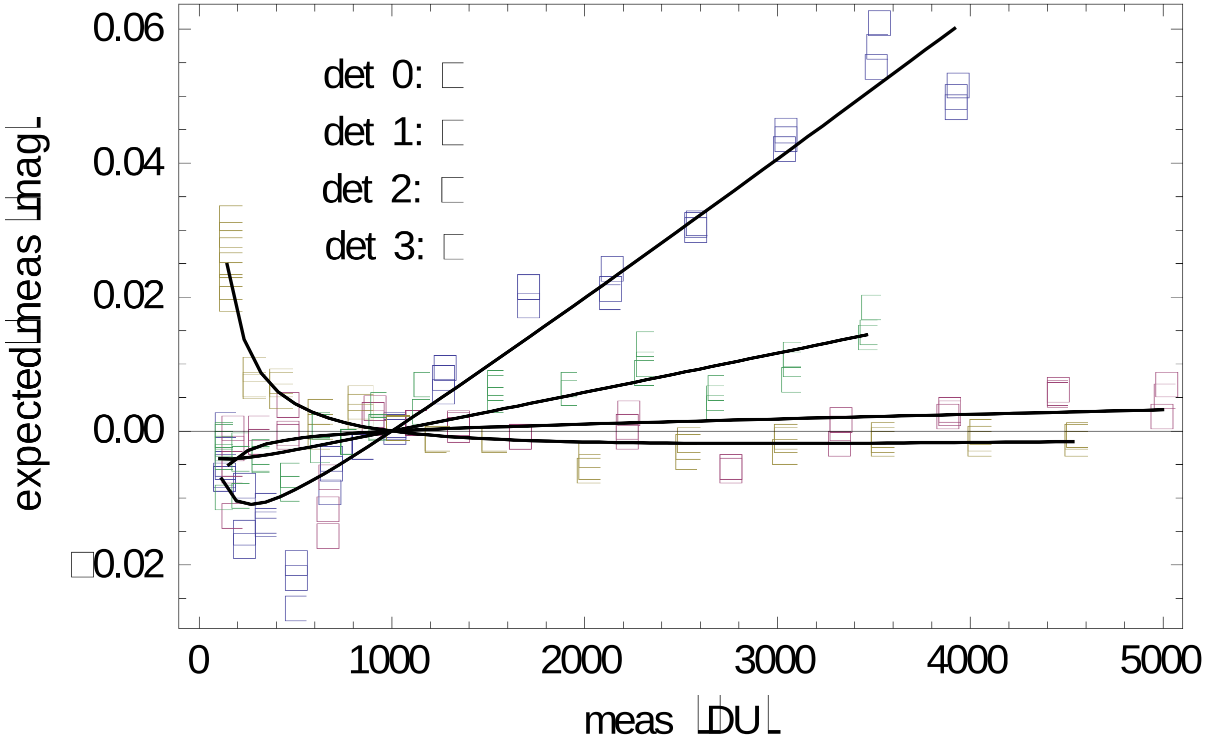


Median intensity of 128×128-pixel tiles for two exposure times. The slope of the line is the ratio of exposure times.

Nonlinearity: measurements

- Sequence: 4 with exposure time t followed by 4 with 60-s exposure to remove drift. Nine values of t. 8.5<t<210s. First image discarded to reduce memory.
  - Measured drift is 3% over 3hr.
- Darks taken
- Source: ambient thermal radiation in cont3 filter (2.2μ)

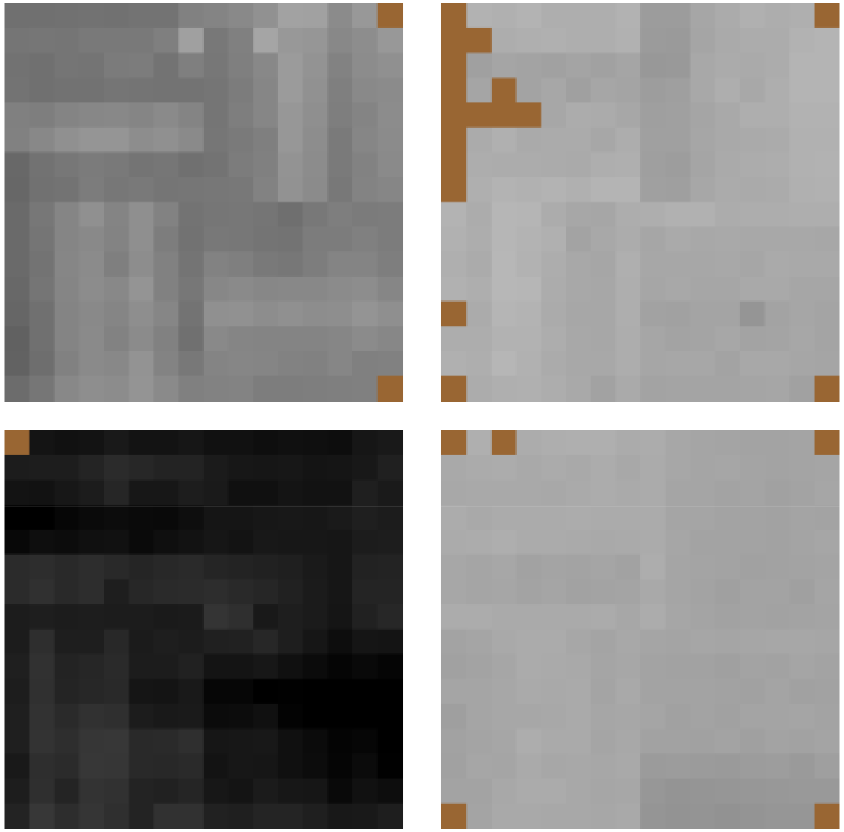
Nonlinearity: Results

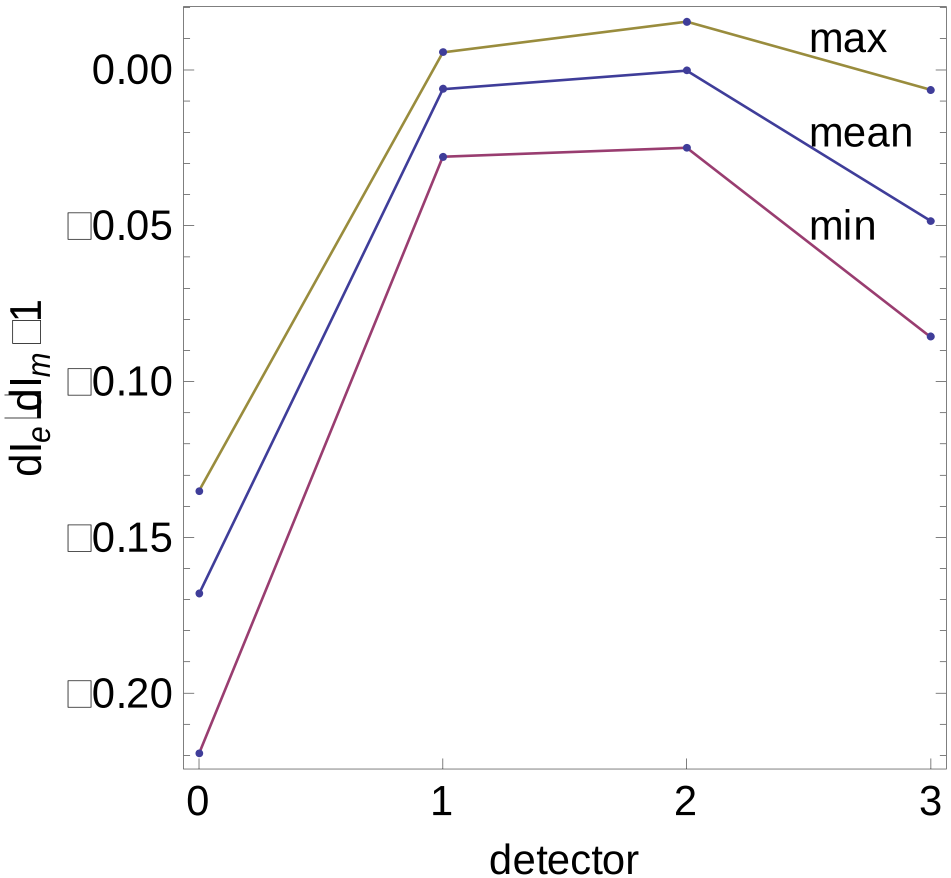


Caption: Nonlinearity at low intensity. The expected intensity is I_e=1000t/t_0, where t is the exposure time and t0 is the time for which I_m=1kDU. The lines are a linear fit of $I_e=a+I_m+bI_m^2$

- Significant nonlinearity in detectors 0 and 3.
- Too much signal at 4000DU compared with 1000DU
  - Opposite sense from usual case.
- Possible fix: Increase pixel time.

Nonlinearity varies across a detector.





Caption: dI_e/dI_m-1 at I_m=10000DU for detectors 0, 1, 2, and 3 starting at the lower left and proceeding counterclockwise

Caption: dI_e/dI_m-1 at I_m=10000DU for detectors 0, 1, 2, and 3. Min, mean, and max are shown

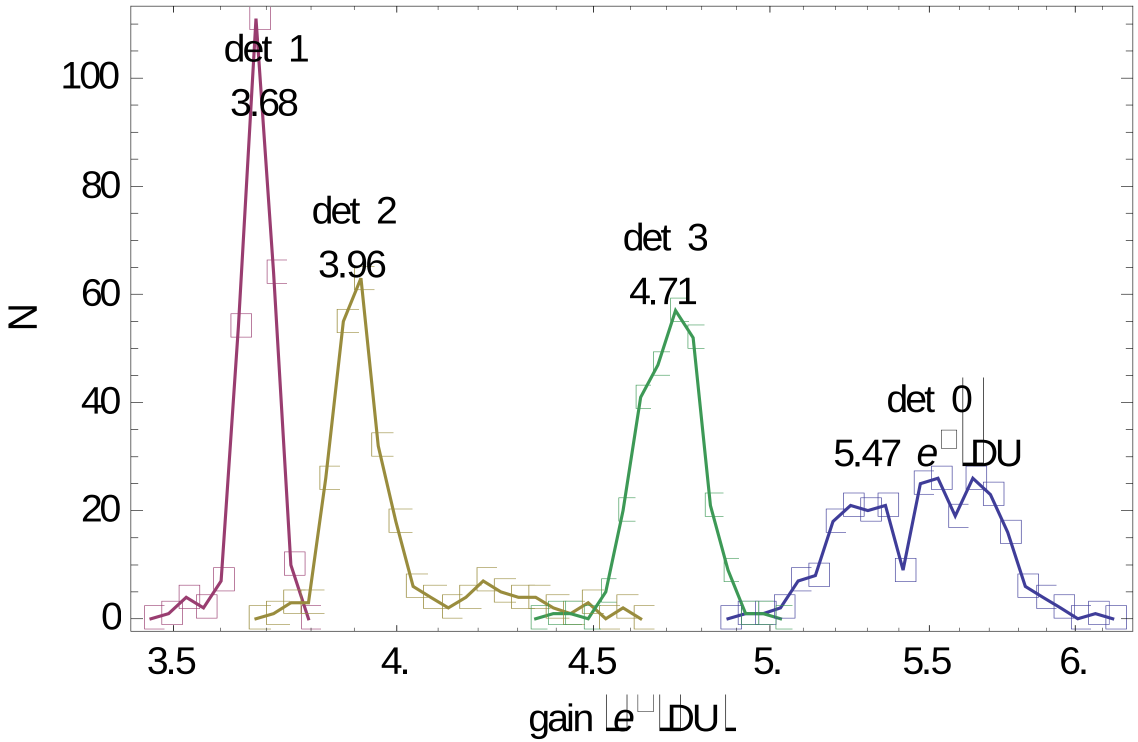
Noise & transfer function

- Variance v and mean m

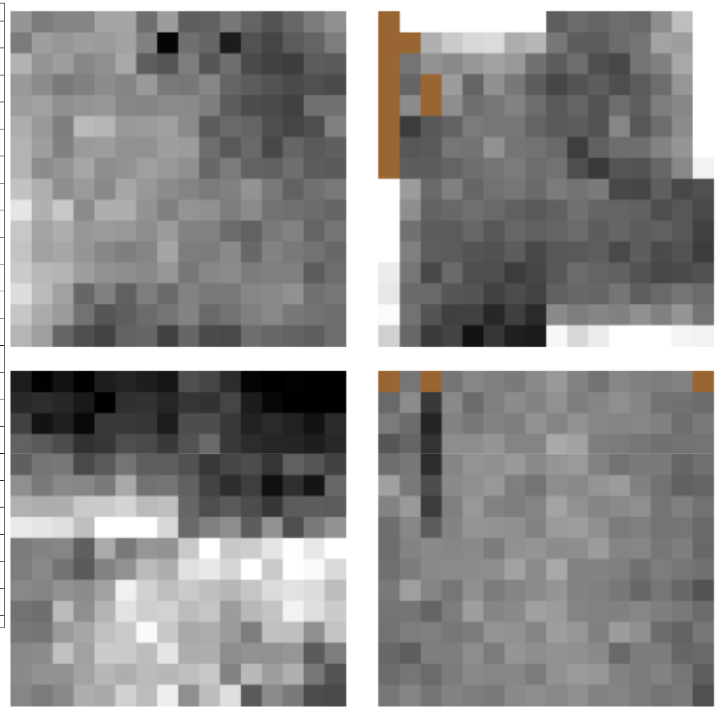
$$v = n^2 + g^{-1}m + c\,m^2$$

  - n detector noise with no signal
  - g gain [e$^-$/DU]
  - c nonlinearity
- Measure noise to determine detector noise, gain, and nonlinearity.
  - No need for stable light source.

Gain is not uniform



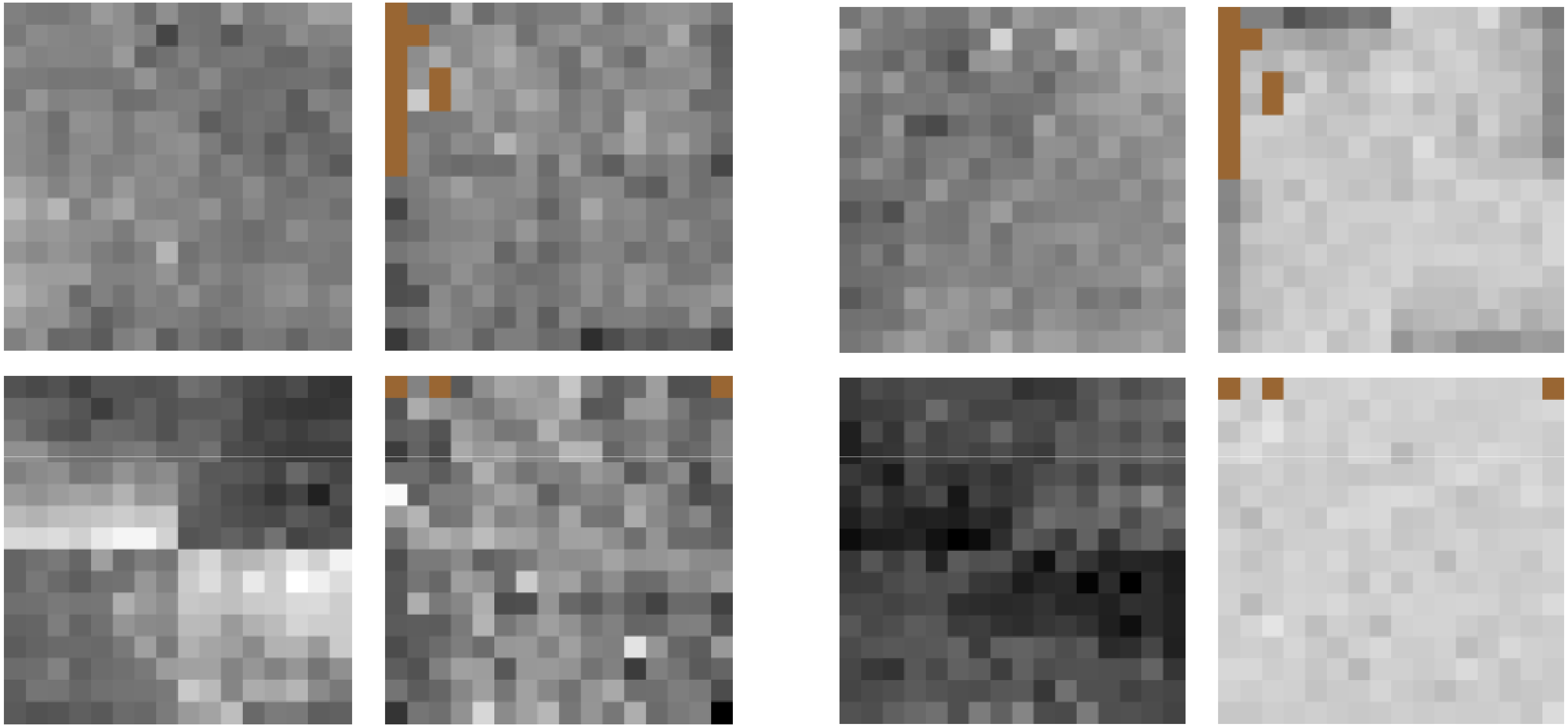
Histogram of the gain for detectors 0–3



Gain map for detectors 0–3 starting in the lower-left and proceeding counterclockwise

- Gain is not uniform. Nonlinearity affects g and c.

Read noise & nonlinearity



Left: read noise. Det 0: 22.6 (lower left), 8.5, 12.7, & 14.9 in counter clockwise order

Right: ratio of the nonlinear to linear response at 10kDU. -0.168, -0.008, -0.028, & -0.093

- Nonlinearity measured in variance-mean confirms that measured by varying exposure time.
- Nonlinearity affects measurement of noise & gain.

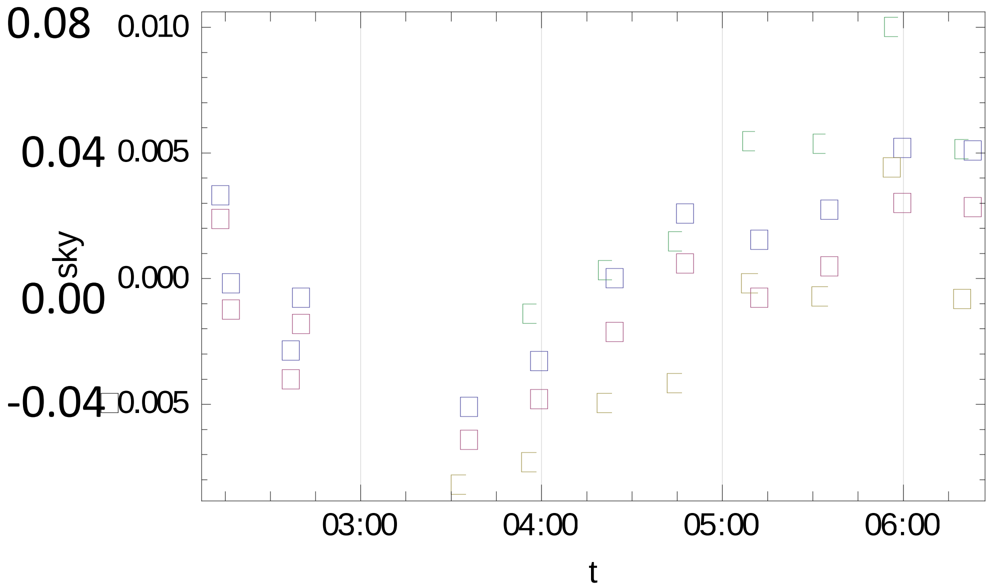
Bad pixels

Detector	bad
0	0.04%
1	0.02%
2 (Engineering grade)	3.4%
3	0.09%

- Problems
  - Low or no response
  - High dark current
  - Higher than expected noise.
- Maps of bad pixels (and Mathematica software for determining them) can be put on web.

Normalize images for changes in sky brightness & transparency

Sky brightness changes over time



- Normalize images by comparing regions of images with overlap.
  - Sky brightness changed 10% over 4hr.
- Normalize transparency using stars in overlap regions.
  - Transparency changed 5% over 4hr

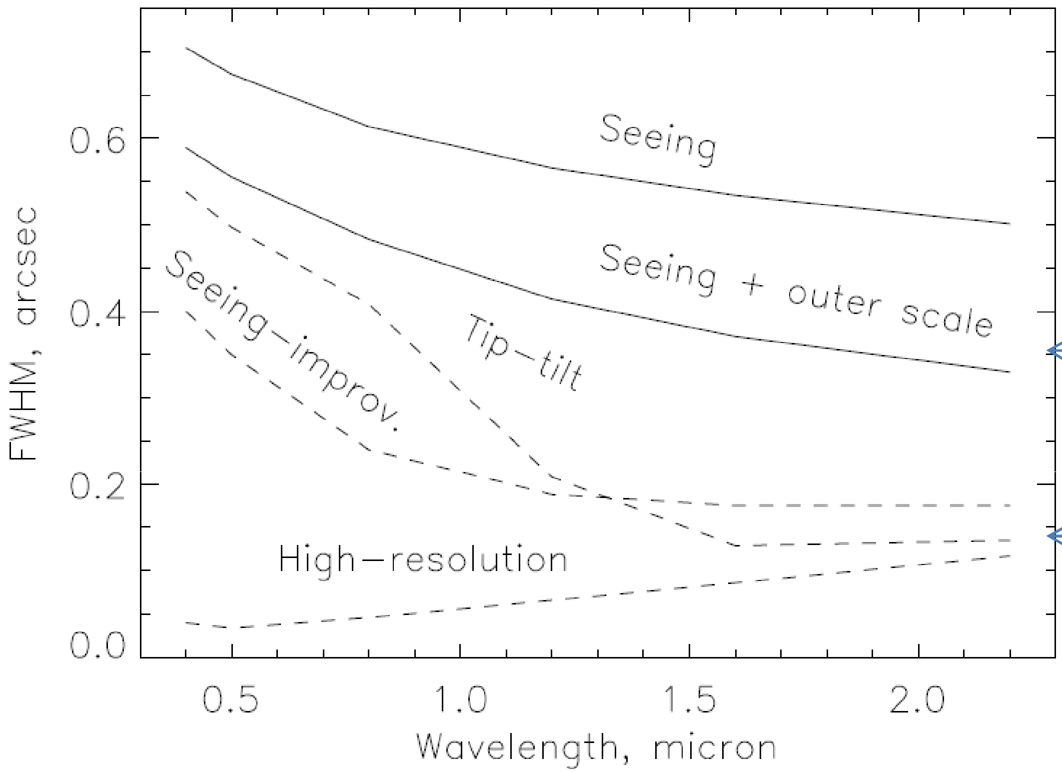
Method for sharing information

- Filter information
- Bad pixel maps
- Nonlinearity
- Detector noise, gain, nonlinearity maps
- Observing FAQ
- Models for sharing information? Volunteers?

Improving Spartan

- NSF proposal, “Fast Infrared Timing for the SOAR Telescope” turned down.
  - 3×3 arcsec field with 47-mas pixels can be sampled at up to 60 Hz.
  - Absolute time (TAI) of the exposure known to 300ns
- How much are you willing to pay to improve the image size by 2.5?

Spartan's potential: 2.5× better seeing



FWHM for median seeing. Tokovinin 2003, Chapter A, SOAR AO: system analysis and simulation

350mas, Spartan, best ever

130mas, expected

- Finish project for determining focus and image aberration using guide star.